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SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2002-162**
David Kirtley (ERC) and Mike Fife (PRSS), "A Colloid Engine Accelerator Concept"

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# A Colloid Engine Accelerator Concept

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**A concept for a colloid engine with an electrodynamic linear accelerator is described. The charged particle source is a standard colloid engine with an extractor voltage that has an AC component. Downstream of the extractor, a series of accelerator gates are biased alternately with an AC voltage such that the charged droplets tend to remain in regions with positive electric fields. Since the droplet speed varies with their position in the accelerator, and the alternating voltage is of a constant frequency, the gate spacing must change with length. This variation in gate spacing may be determined analytically. This paper attempts to predict some of the potential performance advantages and disadvantages of such an engine. Also, design issues are explored, with special attention to potential problem areas.**

## Introduction

Small onboard electric propulsion (EP) thrusters have advantages over chemical engines in applications on small satellites, microsatellites, and nanosatellites. Several types of miniature EP thrusters are currently under development, including field emission thrusters, micro pulsed plasma thrusters, laser ablation thrusters, vacuum-arc thrusters, micro-ion thrusters, and micro-colloid engines. One problem with many of these devices is the requirement of high voltage or otherwise high power supply mass.

Electrostatic devices require a voltage in accordance with their propellant charge-to-mass ratio (q/m), and their specific impulse ($I_{sp}$). However, electrodynamic devices may not be limited by this constraint. This paper explores a concept for an electrodynamic particle accelerator with application to colloid engines.

## Concept

Colloid engines are electric space propulsion devices in which droplets of a conducting fluid, typically doped glycerol or formamide, are electrostatically accelerated through a potential difference. Typically, the charged droplets are extracted from a hollow needle, which is biased with respect to an extractor gate by around 2 kV. When biased beyond its onset voltage the conductive fluid on the needle tip forms a Taylor cone-jet[1]; downstream, the jet breaks up and the particles are extracted. After extraction, the charged droplets may exit the device, or go through a second electrostatic acceleration stage, once again on the order of kV.

The concept presented here differs from a traditional colloid engine by using multiple accelerator gates biased alternately at a much lower AC voltage to linearly accelerate colloid droplets after extraction from the needle. Fig. 1 and Fig. 2 show these configurations.

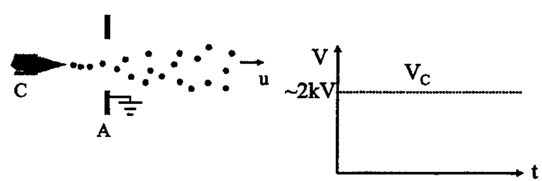


**Fig. 1. Schematic of a typical colloid engine and extraction voltage.**

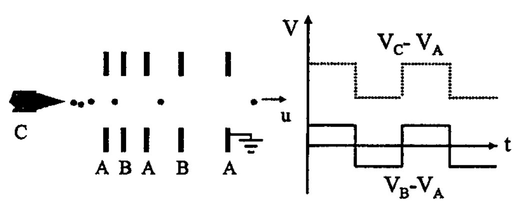


**Fig. 2. Schematic of a colloid engine with electrodynamic linear accelerator and accelerator and extraction voltages.**

The fluid particle droplets are accelerated in alternating sets of gates with an AC voltage. Provided the gate spacing is 'tuned' to the frequency of the extracted droplets and to the AC voltage, this configuration allows an unlimited number of acceleration gates in a thruster.

## Governing Equations and Theory

Critical parameters for the design of the acceleration system are the gate voltage, spacing, and frequency. Following are the governing principles for the colloid linear accelerator. Most are based on simple electrostatics as every particle is in between two charged grids, and the voltage on those grids is constant for the time the particle is between them. Based on colloid technology[2,3] and fundamental electrostatics the specific impulse is:

$$I_{SP} = \sqrt{2\frac{q}{m}\frac{NV_A}{g^2}} \tag{1}$$

Where q/m is the charge to mass ratio, N is the number of gates, and $V_A$ is the acceleration voltage per gate (assuming a square wave and that all gates have the same voltage). Correspondingly, the thrust is:

$$F = \dot{m}I_{SP}g = \dot{m}g\sqrt{2\frac{q}{m}\frac{NV_A}{g^2}} \tag{2}$$

Fig. 3 shows the thruster performance increase by using many ($N$) rather than 1 acceleration gate. For this analysis, the extraction parameters q/m and $\dot{m}$ can be described by empirical solutions[4,5,6] such that a preliminary estimate of performance may be determined using the equations above. Couple this preliminary extractor information with the previous accelerator performance analysis and a good understanding of the system emerges; results are given in Figs 4-5.

Assuming the droplet has initial velocity of zero, the geometry and spacing of the first gate, $X_{G1}$, may be determined simply. $X_{G1}$ depends on the frequency, $f$, and vice versa:

$$X_{G1} = \sqrt{\tfrac{1}{2}\frac{q}{m}V_A\left(\tfrac{1}{f}\right)^2} \tag{3}$$

This gives the gate spacing between the extractor and the first gate. However, gate spacing is not linear along the length of the accelerator, and once the first gate spacing is determined, the rest must be spaced according to the following:

$$X_N = C_{GN}X_{G1} \tag{4}$$

$C_{GN}$ has been numerically computed, and is given versus gate number in Fig. 6.

Using these relationships, it can be shown that voltage can be totally dependent on frequency (for a constant q/m) and independent of gate spacing, i.e. the voltage and Isp can be throttled mid-mission without a geometry change within the acceleration system.

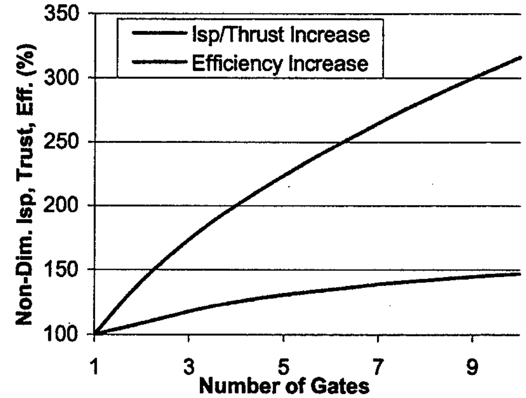


**Fig. 3. Performance increase due to multiple gates versus single accelerator gate. Assumes constant extraction parameters and gate voltages.**

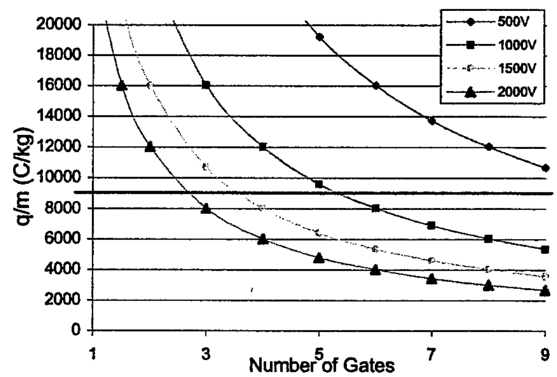


**Fig. 4. Charge-to-mass ratio required for Isp=1000s and $X_{G1}$=1mm. 9000 C/kg is an expected operational target**

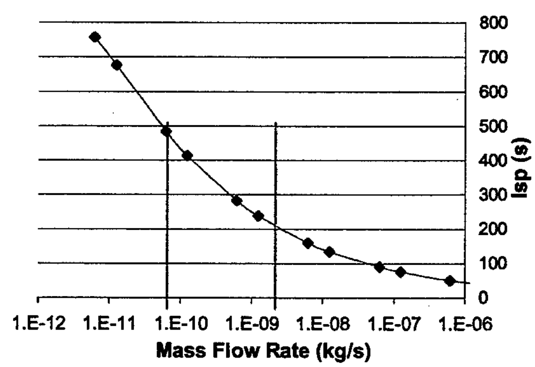


**Fig. 5. Relationship between Isp and mass flow rate for a 5-gate accelerator and extraction at 1500V. Noted is the flow rate region of interest .**

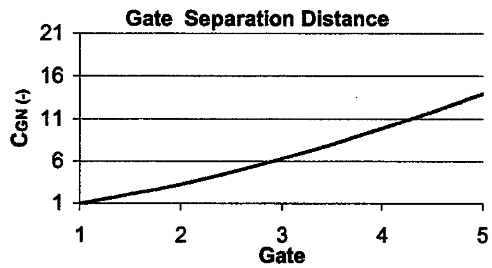


**Fig. 6. Gate separation distance coefficient, CGN, versus gate number.**

This paper discusses a square wave as the accelerator voltage signal, but it may be possible (with a ~5% accelerator efficiency loss) to use a sine wave, thereby eliminating the need for high power rectifier circuits all together.

## Comparison with Traditional Colloid Engines

This concept retains the performance benefits of a colloid thruster, namely potentially high Isp, high acceleration efficiency (70%+), simple acceleration physics, throttleability, and scalability (ability to miniaturize). In addition, the AC linear accelerator allows a reduction in operating voltage and increased variable operating parameters. This may simplify the power processing electronics significantly by a) not requiring a DC rectifier or other complicated switching mechanism, and b) eliminating the presence of high voltages. Potentially, a small oscillator is all that would be required, which could be miniaturized much more easily.

In terms of expected performance, this concept is similar to colloid engines being developed currently[7] and can operate with 70%+ efficiency at Isp's between 500-1500s with 10's of μN per needle. The needles can be arranged in array for to develop thruster capable of mN thrusts. Some penalty must be paid for the additional mass of the accelerator stages, however.

The colloid linear accelerator engine still has the same disadvantages as typical colloid thruster: complicated flow system, potential gate clogging, and beam neutralization requirement. However, depending on the mission, the efficiency and mass savings over other micro-thrusters may balance out.

## Design Complications

Using multiple gates in a colloid engine by itself adds very little design complication, however the pulsed nature of the device does. In order to separate the droplets into groups or individual droplets the extractor must be pulsed, and there is, so far, little empirical data for this process.[8] Also the start and stop transients must all be addressed as to their effect on lifetime (clogging) and efficiency.

Furthermore, the design may be sensitive to droplet q/m. If the droplets do not have a uniform and predictable q/m, the multi-gate accelerator concept will not work properly.

Another design complication may be the high frequencies required. Fundamentally, the system requires frequencies near the exit velocity divided by the gate spacing. For 1mm spacing, and $I_{sp}$ around 1000s, 10+ MHz frequencies are required. Even voltages of around 50V are relatively high for this frequency. One possible approach would be to use piezo-electric oscillators. Nevertheless, this is considered to be a very difficult problem inherent to this concept.

## Conclusions

This paper has attempted to introduce a design for a multi-gate AC colloid thruster that has the potential to decrease complexity and operation voltage of a colloid thruster while retaining their excellent performance characteristics. There are many engineering challenges ahead for this design. However, the concept of the multiple-gate AC linear accelerator is general, and may also be considered for use on other electric propulsion devices. For example, ion engines may be able to benefit more from this technology. In the ion engine case, q/m is more consistent and predictable, therefore eliminating some of the problems mentioned above.

The fundamental advantage of this technology is that it utilizes AC operation and multiple gates to lower the operating voltage, while retaining the performance and throttleability of an electrostatic thruster.

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